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An Investigation
into
The Influence of Moisture in the Steam Economy of the Steam Engine.

June 1902.

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This article is written on the results of a series of experiments undertaken for the purpose of finding what effect on the economy of a plain slide-valve steam engine was produced by introducing by condensation varying quantities of water in the steam supplied to the engine.

This was accomplished by surrounding a portion of the steam pipe with a jacket through which water was circulated at different rates, the regulation being effected by valves in the supply and discharge pipes.

The arrangement of the apparatus is shown in the photograph and sketch. (pages 14-15).

The jacket consists of an iron vessel 16 inches heigh and $6\frac{1}{2}$ inches in diameter screwed to the steam pipe at its upper end and having at its lower end a screwed gland made water-tight by robber packing. The supply and discharge pipes are connected to the jacket at its upper part, the incoming water being led near the bottom of

the vessel by an internal pipe.

In order to obtain an average sample of steam before being partially condensed, a collecting nipple perforated with large holes was screwed completely across the steam pipe somewhat beyond the water jacket, to this nipple was attached a Barrus calorimeter with which the quality of the steam as supplied from the boilers was determined.

The engine tested was a 6"×8" high-speed Weston engine with shaft governor and fitted with a brake for absorbing the power.

The scheme of the experiment was to maintain all conditions as nearly as possible constant, except the quality of the steam, so the engine was run at a constant load and the following observations made:

Engine speed.
Amount exhaust steam condensed.
Amount water injected to jacket.
Gauge pressure.

Indicator cards.

Temperature of steam entering calorimeter.

Temperature of steam leaving calorimeter.

Temperature of water entering jacket.

Temperature of water discharged.

By condensing the steam in a surface condenser the amount supplied per hour was determined. From the dimensions of the engine, the number of revolutions per minute and the mean effective pressure of steam as determined from the indicator cards, the indicated horse-power was found. By knowing the quality of steam before being moistened and the amount of heat taken away from one pound of steam by the water, the quality of the steam supplied to the engine was determined. Having these quantities, the percentage variation of water consumption with the qualities of steam was found and curves plotted showing the results. Also the variation of British Thermal Units consumed per H. P. hour was investigated.

Instruments used.

Head indicator No. 7052 (Crosby)

Crank indicator No 7051 (Crosby)

50 lbs. springs Nos. 7051 and 7052.

Steam gauge No 189439.

Ashcroft revolution counter.

Fairbank's scales Nos. 602695-661927-661931.

Four thermometers reading from 0° to 400° F.

Calibration of instruments.

The steam gauge was calibrated on the Crosby gauge tester, ascending and descending readings having been taken for every 5 pounds, and the corresponding calibration curves plotted.

The indicator springs were calibrated with the aid of the gauge calibration curves in the standard manner.

No calibration of thermometers made as they were interchanged at the middle of each test and so the errors compensated.

The scales were tested by observing the difference of the readings before and after a standard 50 lbs. weight was applied.

Method of making test.

Half-hour runs were made and no observations taken until the conditions of the test became constant.
Water and revolution counter readings were made at intervals of ten minutes.
The first three runs were made without injecting any water into the jacket to obtain a point of comparison to the other tests with wet steam.
The condensed water was allowed to run into buckets to prevent backing up in the condenser.
At the time of starting the test, the pipe carrying the condensed steam was taken from the bucket and allowed to discharge into the tank, the zero reading of the tank scales having been previously taken, two minutes after this, the zero reading of the scales carrying the water-jacket collecting tank was noted by balancing at the proper time; one minute af-

ter the counter was read. The calorimeter tempera-tures, the injection and discharge water temperatures and the gauge pressure were then read at five minutes intervals. In the mean time indicator cards were taken, the load having been kept constant. At about half a minute before the time to take the next reading, the pipe of the condenser was taken out of the tank and allowed to discharge in a bucket, when the time elapsed the pipe was changed to a second bucket and the water of the first one thrown into the tank and weighed ~~with the~~ water for the first ten minutes, then the pipe was allowed to discharge again in the tank and the water of the second bucket thrown in to be weighed at the end of the next ten minutes; two minutes after, the weight of the other tank was balanced and noted; one minute from this the counter reading was taken and the next series of observations made as before.

Method of Working up results.

The following data were used in the calculations:

Cylinder diameter	6".
Piston stroke	8"
Piston rod diameter	$1\frac{1}{8}$"
Area of piston (Head)	28.26 sq. in.
Area of piston (Crank)	27.28 " "
Spring scale (Head)	50.1 lbs.
Spring scale (Crank)	48.5 lbs.
Engine constant (Head)	$\frac{28.26 \times 8}{12 \times 33000} = .000\,5709.$
Engine constant (Crank)	$\frac{27.28 \times 8}{12 \times 33000} = .000\,5511.$

These constants multiplied by the number of revolutions, the spring scale and the mean ordinate of card give the horse-power.

As an example let the test E of April 26th be taken: the mean head ordinate was .666", while the mean crank ordinate was .636" and the mean number of revolutions per minute was 328.3.

The head H.P. $= .000\,5709 \times 328.3 \times 50.1 \times .666 = 6.253.$

The crank H.P. $= .000\,5511 \times 328.3 \times 48.5 \times .636 = 5.588.$

Total H.P = 11.841.

The water consumption per half-hour was obtained by substracting the first reading from the last one and the result checked by adding together the differences of the ten minutes readings.

Water per hour = 2 (525 - 224) = 602 lbs.

The quality of steam as supplied from the boilers was found as follows:

The mean gauge pressure was 98.5 which corrected by aid of the gauge calibration curve was reduced to 98.3, then the absolute pressure equals

$$98.3 + 14.7 = 113 \text{ lbs.}$$

The temperature corresponding to this pressure was 336.55°F (Peabody's tables). The average temperature of the upper thermometer was 334°F, then there is an error of 336.55 - 334 = 2.55° and since the upper and lower thermometers were interchanged at the middle of each test, this is considered to be loss due to radiation. The lower temperature was 277.8°F and as the same loss is assumed to occur at this therm

meter the probable temperature would be $277.8 + 2.55 = 280.35°$ which showed that the steam leaving the calorimeter was superheated since the temperature at atmospheric pressure is 212°; this superheating resulted from the sudden drop of pressure of steam in passing the calorimeter diafragm.

Now calling x the quality of steam, q the heat necessary to raise one pound of the liquid to the temperature corresponding to a given pressure, r the heat of vaporization at that pressure, the heat in one pound mixture entering calorimeter was: $q_1 + x_1 r_1$. If T_{sup} is the absolute temperature of steam leaving calorimeter, T_{sat} that corresponding to atmospheric pressure and .48 the specific heat of superheated steam at constant pressure, we have that the heat in one pound leaving calorimeter was:

$q_2 + r_2 + .48(T_{sup} - T_{sat})$. As no loss by radiation in passing the diafragm is assumed:

$$q_1 + x_1 r_1 = q_2 + r_2 + .48(T_{sup} - T_{sat}).$$

and from this we got the value of x_1:

$$x_1 = \frac{\lambda_2 + .48(T_{sup} - T_{sat}) - q_1}{r_1}$$

in which λ equals the total heat or $q+r$. Substituting values:

$$x_1 = \frac{1146.6 + .48(280.35 - 212) - 307.30}{877.34} = .9941.$$

The heat taken away by the water per pound of steam supplied to engine was then found: 4.36 lbs of water were circulated per minute through the jacket, the temperatures of entrance and discharge of this water having been 76.6° and 203.6° F; then the heat carried out per minute was:

$$4.36(q_d - q_e) = 4.36(172.3 - 44.69) = 556.34 \text{ B.T.U.}$$

In the same time 10.03 lbs of condensed steam were collected in the tank, then the heat off per pound was:

$$\frac{556.34}{10.03} = 55.46 \text{ B.T.U.}$$

In taking out this heat some of the steam was condensed and therefore this heat equals the heat

of vaporization multiplied by the difference between the original quality and that after condensation or

$$55.46 = r_1(x_1 - x_2)$$

from this:

$$x_2 = x_1 - \frac{55.46}{r_1} = .9941 - \frac{55.46}{877.34} = .93089$$

Curves were plotted showing the relation between the qualities of steam and the following quantities:

1. Net water consumption per H.P. hour.

$$W = \frac{602}{11.841} = 50.845 \text{ lbs.}$$

2. Dry steam consumption per H.P. hour.

$$Wx_2 = 50.845 \times .93089 = 47.331 \text{ lbs.}$$

3. Equivalent dry steam consumption per H.P. hour or the water consumption on the heat basis. (Case a)

$$W\frac{q_1 + x_2 r_1}{\lambda_1} = 50.845\,\frac{307.30 + .93089 \times 877.34}{1184.64} = 48.242.$$

4. Equivalent dry steam consumption. (Case b).

$$W\frac{q_1 + x_2 r_1 - q_{212}}{\lambda_1 - q_{212}} = 50.845\,\frac{307.30 + .93089 \times 877.34 - 180.8}{1184.64 - 180.8} = 47.773$$

5. British Thermal Units supplied per H. P. hour.

$$W(q_1 + x_2 r_1) = 50.845(307.30 + .93089 \times 877.34) = 57146.$$

As the results of the investigations on the first three basis showed a percentage variation in the wet tests of 2.8, 2.7 and 2.6 respectively, the last two methods were tried with the purpose of seeing if the economy of the engine on those basis could be brought to a more constant value, the resultant variations having been 2.5% and 2.7%, so the smallest variation was obtained on the basis of equivalent dry steam (case b).

Conclusions.

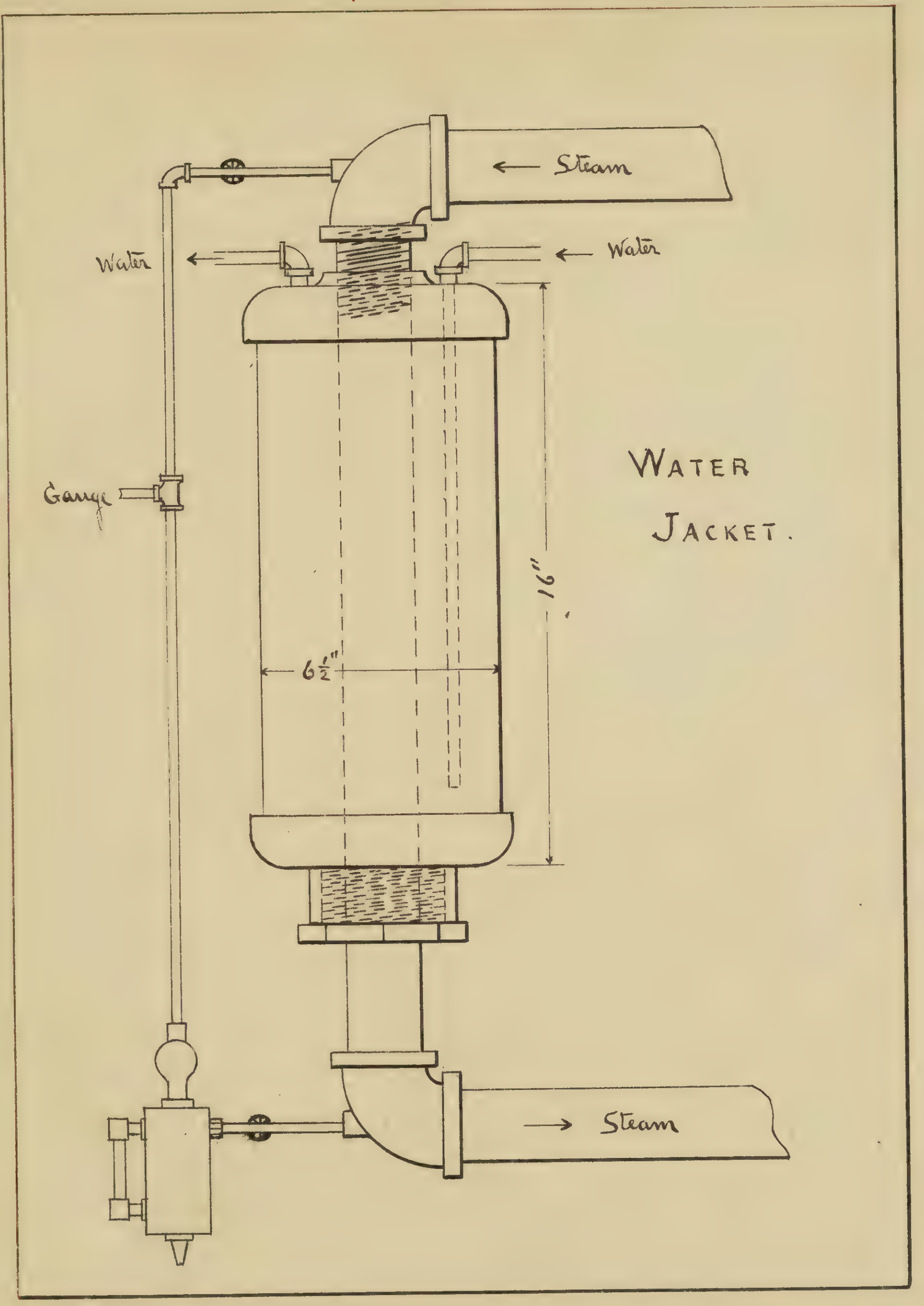
The qualities of steam obtained were practically constant for different rates of water circulation through the jacket, while the consumption of the engine on the several basis showed the already stated percentages of variation.

This shows that there is no fixed relation between

the economy of the engine and the qualities of steam supplied. No doubt, the matter needs of further investigation although an effort was made to obtain consistent results.

The object of this research was to confirm the statement made in a paper by Prof. Carpenter (A.S.M.E. Vol 15. p.438) that the economy of an engine as regards dry steam was practically constant for different qualities of steam used.

In order to obtain different qualities of steam it could be suggested the partially throttling of the discharge water as to let it boil and so obtain an additional raise in temperature and therefore vary the amount of heat taken away.


Steam
Water
Water
WATER
JACKET.
Gauge
16"
6½"
Steam

Calibration of Gauge
No 18939.

True Pressure	Ascending	Descending	True Pressure	Ascending	Descending.
10	9.5	10.1	60	60.0	60.0
15	14.0	15.1	65	65.0	65.1
20	19.0	20.0	70	69.3	70.0
25	24.0	25.0	75	74.7	75.0
30	29.7	30.0	80	79.4	79.7
35	34	34.8	85	83.7	84.0
40	39.5	39.5	90	89.5	89.6
45	44.5	44.7	95	94.5	95.5
50	49.5	49.9	100	100.	100.2
55	54.9	55.0	105	105.0	105.5

Calibration of Indicator Springs.

Nº 7051 Ascending.				Nº 7052 Ascending.			
Gauge pressure	True pressure	Distance from 10 mark	Scale	Gauge pressure	True pressure	Distance from 10 mark	Scale.
90	90.3	1.62"	49.1	90	90.3	1.59"	50.1
80	80.5	1.43"	48.8	80	80.5	1.40"	49.9
70	70.7	1.20"	49.2	70	70.7	1.19"	49.6
60	60.0	1.01"	48.8	60	60.0	.98"	50.4
50	50.4	.81"	49.1	50	50.4	.79"	50.3
40	40.5	.62"	48.2	40	40.5	.59"	50.6
30	30.5	.41"	48.5	30	30.5	.38"	52.3
20	20.9	.20"	51.5	20	20.9	.19"	54.2
10	10.6	0	—	10	10.6	0	—
Mean spring scale 49.1 lbs.				Mean spring scale 50.92 lbs.			

April 26th — Test A.

Time	Condensed Water	Time	Counter	Gauge	T_1	T_2
12.15	356	12.16	2744			
12.25	447	12.26	6342	99 96	334 332	284 284
12.35	533	12.36	9266	96 95	332 334	282 283
12.45	623	12.46	2513	97 98	334 334	284 283

Test B.

Time	Condensed Water	Time	Counter	Gauge	T_1	T_2
3.02	196	3.04	6611			
3.12	292	3.14	9886	94 90	328 328	278 277
3.22	384	3.24	3171	91 91	328 328	277 276
3.32	481	3.34	6454	94 95	327 328	279 279

Test C.

Time	Condensed Water	Time	Counter	Gauge	T_1	T_2
4.30	177	4.32	8572			
4.40	274	4.42	1850	96 95	328 328	280 282
4.50	363	4.52	5133	94 92	326 328	280 280
5.00	453	5.02	8430	95 96	330 332	276 276

April 26th. Test D.

Time	Condensed Water	Circulated Water	Counter	Gauge	T_1	T_2	T_3	T_4
10.35	182	130	—					
10.45	287	178	5204	95 96	326 328	278 278	176 184	74 76
10.55	392	228	8482	98 98	330 330	279 279	188 188	74
11.05	492	275	1774	100 100	332 331	280 280	194 194	74

Test E.

Time	Condensed Water	Circulated Water	Counter	Gauge	T_1	T_2	T_3	T_4
11.40	224	174	3089					
11.50	338	218	6381	96 96	330 332	276 278	198 202	76 76
12.00	423	262	9655	100 101	336 336	278 278	204 206	76 76
12.10	525	305	—	99 99	336 334	279 278	206 206	78 78

April 28th. Test F.

Time	Condensed Water	Circulated Water	Counter	Gauge	T_1	T_2	T_3	T_4
12.11	174	284	8204					
12.21	290	346	1421	100 100	336 335	278 278	168 164	70 70
12.31	395	402	4644	100 99	335 332	278 276	165 184	68 70
12.41	499	452	7852	98 98	332 330	276 274	186 184	70 70

April 28th. Test G.

Time	Condensed Water	Circulated Water	Counter	Gauge	T_1	T_2	T_3	T_4
2.35	191	168	1021					
2.45	300	274	4310	98 98	330 328	282 282	130 130	72 74
2.55	405	381	7602	95 97	326 328	280 279	132 132	74 74
3.05	508	487	0882	98 101	330 332	278 279	136 137	78 78

Test H.

Time	Condensed Water	Circulated Water	Counter	Gauge	T_1	T_2	T_3	T_4
3.35	197	156	3892					
3.45	308	234	7182	100 100	334 335	278 278	156 158	82 82
3.55	420	304	0467	101 100	335 336	278 277	166 170	82 84
4.05	528	370	3758	102 101	336 336	278 278	171 171	84 84

Test I.

Time	Condensed Water	Circulated Water	Counter	Gauge	T_1	T_2	T_3	T_4
4.30	185	142	6104					
4.40	291	268	9389	95 95	328 328	281 282	132 132	84 84
4.50	398	399	2694	100 100	328 330	282 282	132 130	83 83
5.00	504	539	5972	98 98	330 330	282 283	128 128	83 82

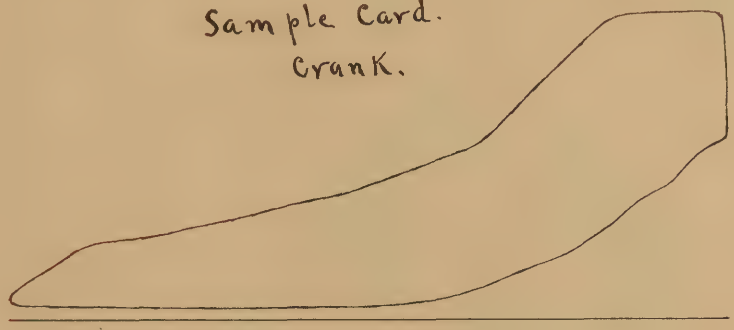
Mean Readings.

Rev. per min.	Condensed Water per hour	T_1	T_2	Gauge	Circulated Water per. min.	T_3	T_4
325.6	534	333.3	283.3	96.8	—	—	—
328.0	570	327.8	277.6	92.5	—	—	—
328.6	552	327.0	279.0	94.6	—	—	—
328.5	620	329.5	279.0	97.4	4.83	187.3	74.5
328.3	602	334.0	277.8	98.5	4.36	203.6	76.6
321.6	650	333.3	276.6	99.1	5.60	175.1	69.6
328.7	634	329.0	280.0	97.8	10.63	132.8	75
328.8	662	335.3	277.8	100.6	7.13	165.3	83
328.9	638	329.0	282.0	96.3	13.23	130.3	86.3

Calorimeter Log.

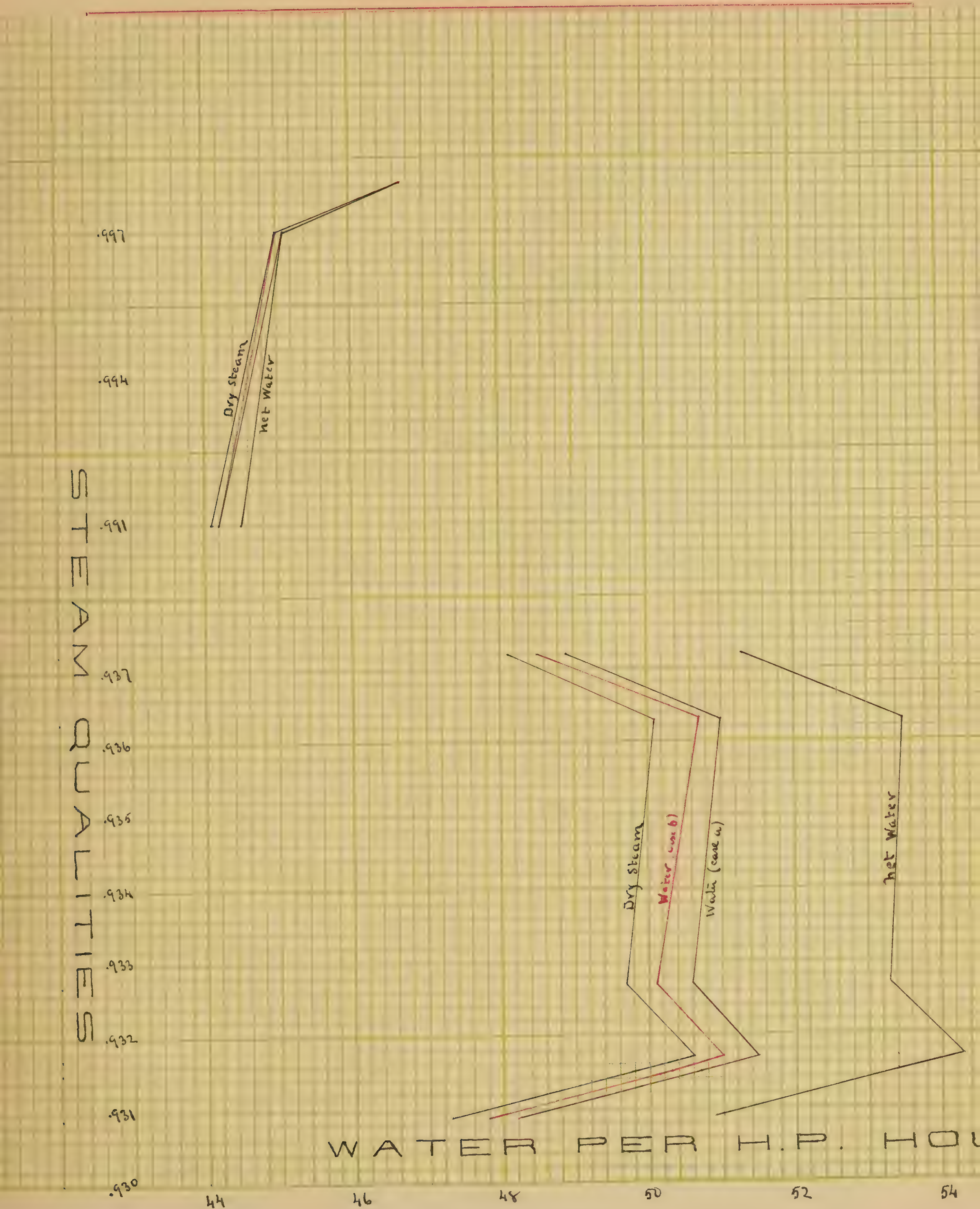
Test	Correct Pressure	Absolute Pressure	Higher Temperature	Radiation loss	Lower Temperature	Quality x_1
A	96.8	111.5	335.56	2.26	285.56	.9975
B	92.0	106.7	332.31	4.57	282.11	.9914
C	94.5	109.2	334.01	7.01	286.01	.9981
D	97.3	112.0	335.89	6.39	285.39	.9978
E	98.3	113.0	336.55	2.55	280.35	.9941
F	99.0	113.7	337.02	3.72	280.32	.9941
G	97.7	112.4	336.15	7.15	287.15	.9979
H	100.5	115.2	337.98	2.68	280.48	.9937
I	96.3	110.0	334.56	5.56	287.56	.9987

Sample Card.
Crank.

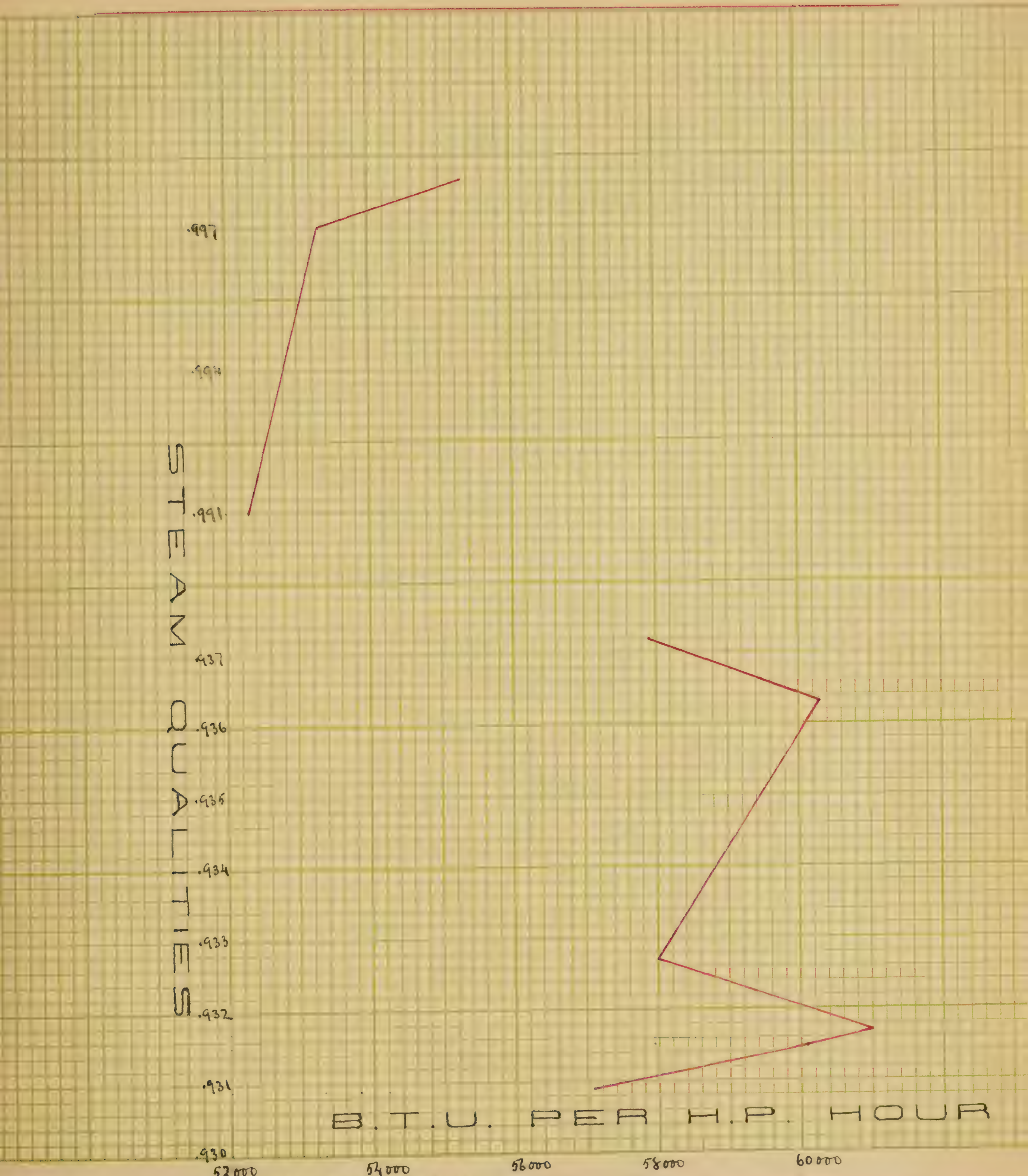


Results of Tests.

Test	I. H. P.	B.T.U. Taken away per minute	B.T.U. abstracted per lb. steam	Quality X_2	Water per H.P. hour	Dry Steam per H.P. hour	Water on heat basis (case a)	Water on heat basis (case b)	B. T. U. per H.P. hour
A	11.834	—	—	—	45.140	45.028	45.058	45.042	53361
B	12.807	—	—	—	44.496	44.113	44.213	44.163	52320
C	11.809	—	—	—	46.740	46.651	46.674	46.662	55252
D	12.078	547.24	53.13	.93723	51.324	48.100	48.935	48.504	57922
E	11.841	556.34	56.46	.93089	50.845	47.331	48.242	47.773	57146
F	11.981	593.05	54.76	.93165	54.256	50.551	51.510	51.032	61027
G	11.876	615.36	58.27	.93151	53.412	49.753	50.728	50.271	60106
H	12.434	589.16	53.41	.93274	53.258	49.674	50.607	50.132	59970
I	11.929	582.79	54.82	.93631	53.479	50.072	50.950	50.725	60321



STEAM QUALITIES
WATER PER H.P. HOU
.997
.994
.991
.937
.936
.935
.934
.933
.932
.931
.930
44
46
48
50
52
54
Dry steam
Wet Water
Dry steam
Wet Water



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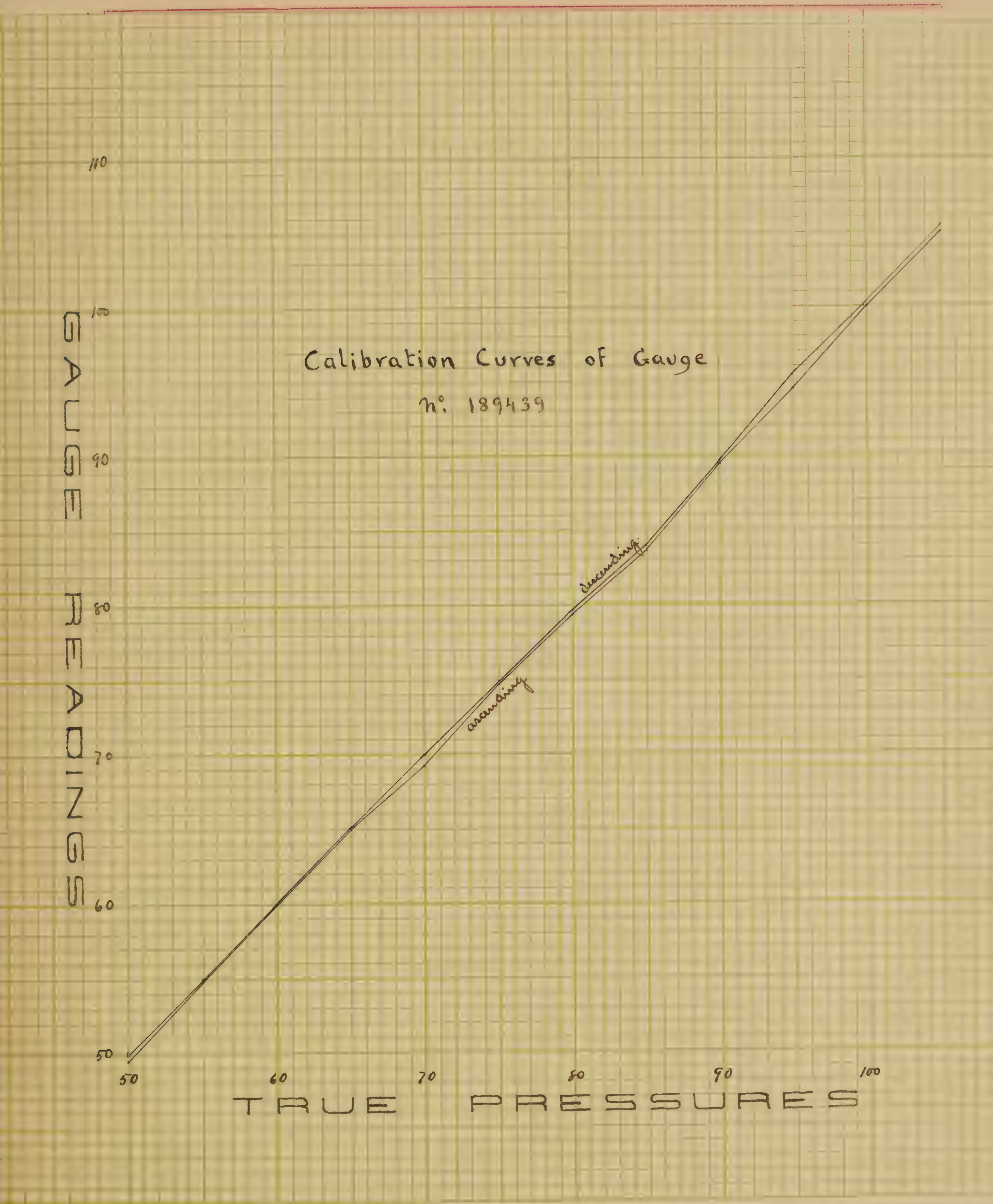
Calibration Curves of Gauge
No. 189439
GAUGE READINGS
TRUE PRESSURES
110
100
90
80
70
60
50
50
60
70
80
90
100
ascending
descending